RESEARCH DEPARTMENT

The subjective assessment of multiple co-channel television interference

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THE BRITISH BROADCASTING CORPORATION
ENGINEERING DIVISION

RESEARCH DEPARTMENT

THE SUBJECTIVE ASSESSMENT OF MULTIPLE CO-CHANNEL TELEVISION INTERFERENCE

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SUMMARY

The increase in protection ratio required by a number of simultaneous constant-level interfering signals, compared with the ratio required for a single interfering signal, is considered. The results of some subjective tests are presented, and formulae are deduced to enable the additional protection ratio to be calculated, for related and unrelated types of interference.

1. INTRODUCTION

In planning the u.h.f. television service, it is becoming increasingly important to be able to assess the probable effects of a number of simultaneous interfering signals.* The problem may be complicated by the variation of the signals with respect to time and location, as a result of propagation effects. Also, the subjective effect of the interference depends on the picture content and the exact carrier-frequency differences between the interfering signals.

The effect of time and location variations has been studied elsewhere[1,2,3,7] and will not be considered here. In many practical cases such variations are sufficient to permit an analysis of the problem by assuming that, at any instant of time, the subjective impairment is caused by only one of the interfering signals. On the other hand, for some practical situations it is desirable to find the extent to which the individual protection ratios should be increased when all the interfering signals are continuously present. This report is concerned with the latter situation, and presents the results of some subjective tests carried out in the laboratory. Based on this work, a suitable law of addition of interferences is suggested.

Previous experiments[10] on co-channel interference with PAL colour transmissions showed that the impairment of the luminance signal is usually more important than that associated with colour; the present tests were therefore carried out with monochrome pictures only.

2. ADDITION OF UNRELATED INTERFERENCES

2.1. Experimental Results

Interferences producing different types of subjective impairment will be called 'unrelated interferences.' For example, the horizontal bar pattern produced by a transmission with, say, a two-thirds line-frequency offset is considered to be unrelated to the flicker produced by a transmission with nearly zero offset. It seems reasonable to suggest that such unrelated interferences combine according to an equivalent power addition law. Thus, if two interferences causing equal subjective impairment (but not necessarily of equal absolute powers) when applied singly are added, each of the interfering signals would have to be reduced by 3 dB in order to produce, together, the same subjective impairment. As a check upon the validity of this assumption, a subjective test was carried out involving the addition of a two-thirds line-frequency precision offset interference and a 2 Hz offset interference. Each vision carrier was modulated by the same picture as the wanted signal (the 'girl in studio' slide), but the modulating signal for the interfering carriers was delayed by 87 μs, thus causing the interfering synchronizing pulses to occur during the picture period of the wanted signal.

Each interference separately was set at a level corresponding to a subjective impairment of approximately grade 2·5 on the EBU impairment scale.*

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* For convenience, 'interfering signal' may sometimes be referred to as an 'interference'.

* Grade 1 = Imperceptible.
Grade 2 = Just perceptible.
Grade 3 = Definitely perceptible, but not disturbing.
Grade 4 = Somewhat objectionable.
Grade 5 = Definitely objectionable.
Grade 6 = Unusable.
Fractional grades represent the mean value of the grades given by a group of subjects.

The two interferences were then applied simultaneously, and the level of the combined interferences was reduced until the same degree of impairment was obtained. Six observers (one at a time) made the assessment. The mean reduction was 2·34 dB, with a standard deviation of 1·25 dB. Applying Student's 't' test to these figures indicates that the difference between this observed mean and the suggested 3 dB is not statistically significant.

As a final check, one 'experienced observer' (the author) carried out a number of tests, using still and moving pictures, combining a nearly zero offset interference with other offsets, including precision two-thirds line, non-precision two-thirds line, and 500 Hz, and satisfied himself that for two interferences, the power addition law is a good working rule to apply. Further tests showed that two non-precision two-thirds line interfering signals also combine in this way when the frequency difference between these signals is greater than a few hertz. It is reasonable to suggest that a similar conclusion will apply for more than two unrelated interferences.

It should be emphasized that this law relates to the case in which the separate interferences produce subjectively equal impairments, but the interfering signals may have different relative levels.

2.2. Previous Work

It is inevitable that any general law of this nature can only be approximate. Amongst other factors, it will depend upon the slope of the subjective impairment/protection ratio curve, and it will depend to some extent upon the degree of impairment at which the law is assessed. A somewhat sophisticated approach is used by Prosser, Allnatt and Lewis[4,5]. Their work is not specifically related to co-channel interference, but has been applied to a number of other forms of picture impairment. The approach should, however, be applicable to the present problem. A five-point quality-grading scale is used, with associated numerical values ranging from 0 to 1, and the curve relating quality to 'impairment' (in this context, 'impairment' is used to denote the equivalent of 'interfering signal level' in the present report), is approximated by a logistic function,

$$p = \frac{1}{1 + \exp\{(x-M)/S\}}$$

where p = quality index

x = level, in dB, of the 'impairment'

M = the level of 'impairment' which produces a subjective quality grading of 0·5. (A quality grading of 0·5 corresponds roughly with grade 3·5 on the EBU subjective impairment scale).

S = an index proportional to the reciprocal slope of the curve at the point of inflection of the quality grading curve.

For two unrelated 'impairments' applied simultaneously, p is then expressed by

$$p = \frac{1}{1 + \exp\{(x-M_1)/S_1\} + \exp\{(x-M_2)/S_2\}}$$

If it is now assumed that $M_1 = M_2$, and $S_1 = S_2$, and that the level of each of the combined 'impairments' is reduced to x' so as to obtain the same quality grading as for a single 'impairment' at level x, it can easily be shown that

$$x' = x - S \log_e 2$$

Extending this to n simultaneous 'impairments' we find that $x' = x - S \log_e n$.

One of the assumptions inherent in this approach is that the addition law is uniquely determined by S, i.e., by the slope of the curve of grading versus interfering signal level. This may not be valid, so that the law must be regarded as a practical approximation. The case $S = 10 \log_{10} e = 4{\cdot}34$ dB corresponds to a power addition law. Prosser et al.[4] give the results of tests of the subjective effect of a 2 μs echo, and for this case $S = 4{\cdot}8$ dB. For another test[8] concerning the effect of flat-spectrum random noise upon monochrome television pictures, a case for which power addition must apply, S was 4·3, thus agreeing well with the predicted value. For the case of noise on colour pictures,[9] however, flat-spectrum noise gave $S = 3{\cdot}4$, which, for two interferences, would give an error of 0·6 dB compared with a power addition law. Bearing in mind the inevitable sources of experimental error, one might well choose a general value for S, based on this limited number of cases, and for this purpose 4·3 dB would not be greatly in error; this therefore supports the hypothesis that power addition is a reasonable law to apply.

Further evidence is available[6] which relates to the addition of up to four forms of distortion, but only two of these forms (viz. single echo and random fluctuation noise) can be expressed in terms of a decibel scale. For this particular addition of impairments, it is found that the impairment increases by approximately one subjective grade.

From a subjective impairment curve relating to random noise, this represents a required reduction in level of about 5 dB. In this case, therefore, the 'power addition' law would be in error by 2 dB. As the scatter in the results obtained in this reference is not known, the significance of this error cannot be assessed, but it must be accepted as a warning that predictions based upon a power addition law may be in error by this amount.

3. ADDITION OF RELATED INTERFERENCES

3.1. General Discussion

In the case of completely correlated interferences (such as interferences having exactly the same carrier offset, identical pictures and modulation delays), the voltages, instead of the powers, will add linearly at locations where the carriers are in phase. In any practical case, this will not occur continuously. 'Related' interferences are those producing the same type of visual effects which are nearly but not completely correlated over a large proportion of the picture. For example, two precision two-thirds line-frequency offset interferences, or two precision zero offset interferences, are considered to be related because they produce patterns of similar form and dimensions. On the other hand, a precision zero offset interference and a precision two-thirds line-frequency offset are unrelated, since they produce interference patterns of different types. Moreover, all non-precision offset interferences, whether the offset is zero or two-thirds line-frequency, may be regarded as unrelated, because for most of the time they produce patterns of different dimensions which do not correlate closely over a large area of the picture. Thus it should be understood that, when discussing related interferences, it is implied that the offsets are precisely controlled.

In a perfectly linear system, it might be expected that related interferences, averaged over a reasonable time, would again tend to add on a 'power' basis. In practice, however, non-linearities cause beat effects between the interferences, visible as brightness variations having a coarse structure. These may be more objectionable than the type of impairment produced by the individual interferences. A typical example is the addition of two interfering signals with two-thirds line-frequency offsets, the actual offsets differing by, say, 2 Hz. With moderate or severe degrees of impairment, the characteristic horizontal bar pattern produced by the interferences is accompanied by a 2 Hz luminance beat which can be more noticeable than the bar pattern. One source of non-linearity is the display tube, which has a nearly square-law relationship between the applied voltage and the light output. Non-linearity in the detector can also contribute.

Because the degree of non-linearity, upon which the beat effect depends, will vary with the level of the interference, the law of addition of multiple related interferences will also vary with this level. For the same reason, the subjective effect varies more with picture content than it does with a single interference. It is therefore very difficult to give a meaningful quantitative addition law for related interferences, but by considering particular cases it is possible to suggest a law which can be used as a rough guide.

3.2. Subjective Tests

A number of subjective tests were carried out to assess the effect of adding several two-thirds line-frequency precision offset interferences. The interferences took the form of c.w. signals injected into the video chain. This is, of course, a somewhat artificial condition, but was adequate for the purpose; it had the advantage of simplicity and kept the number of possible variable factors to a minimum. A number of interfering signals was available, in addition to a 'reference' interference. The latter was kept at a constant level throughout the test. The observer could switch the interference from the test condition to the reference and, for each case of multiple interference examined, the level of this interference was adjusted until the observer assessed the degree of subjective impairment to be the same as that produced by the reference interference.

Two series of tests were carried out. For the first series (Tests 1 to 3) the wanted picture was a woman's head against a white background. The viewing distance was three times the picture height. This viewing distance is somewhat less than the usual distance, but was adopted for this series of tests in an attempt to obtain more reliable comparisons between two interference conditions. Each interfering c.w. signal was adjusted to be within 1 Hz of 10,400 Hz so as to represent the effect of optimum two-thirds line-frequency offsets. The number of interfering signals was varied from one up to a maximum of seven. The video monitor was synchronized from a separate unimpaired source. The peak brightness of the monitor tube was 55 candela/m^2, and the ambient illumination was such that the brightness of a white card in front of the screen was 4·3 candela/m^2. There were seven observers for Test 1, but only four for Tests 2 and 3. In Test 1, the levels of all the interfering signals were equal; in Test 2, the first interference was 6 dB greater than the remaining equal interferences. In Test 3, the levels were in descending 2 dB steps.

A second series of tests was carried out in a similar manner to the above, but in this case a different wanted picture ('girl in studio') was used, the viewing distance was five times the picture height and the frequency tolerance of the interfering signals was ±2 Hz. Apart from these differences, the conditions of Tests 4 to 6 correspond with those of Tests 1 to 3 respectively. Seven observers were used for each test. The tests were carried out for up to five interfering signals.

3.3. Test Results

The results of all the tests are summarized in Table 1.

TABLE 1

No. of interfering signals	Mean change in level, dB, required to produce same subjective impairment as reference					
	Test No.					
	1	2	3	4	5	6
1	+0·9	+0·5	−1·0	+1·4	+1·1	−2·1
2	−4·1	−2·2	−5·0	−3·4	−0·3	−4·0
3	−5·0	−5·5	−6·5	−6·0	−2·0	−6·3
4	−7·1	−6·2	−8·0	−7·9	−3·1	−7·4
5	−7·6	−7·2	−7·2	−8·1	−3·0	−8·0
6	−10·0	−6·5	−8·2			
7	−10·9	−7·7	−8·0			

Ideally, the change in level for one interference should be 0 dB. Departure from this may arise from a genuine difference between the interference and the reference (such as a slight difference in frequency), instrumental errors or inevitable spread in the subjective assessments.

The best estimate of the population standard deviation for these tests is 1·8 dB. The standard error of the mean is 0·7 dB for all the tests except 2 and 3, for which it was 0·9 dB. Hence, applying Student's 't' test to the single-interference figures, the deviation of their mean from the expected zero cannot be considered as significant.

3.4. Laws of Addition of Related Interferences

For unrelated interferences it has been seen that a power addition law can be applied with sufficient accuracy, and it is felt that no advantage is obtained by using the somewhat more complicated law proposed by Prosser et al. In applying the power addition law, it must be remembered that the 'power' of each interference must be 'normalized' to take account of the appropriate protection ratio for a given subjective impairment, and it is therefore convenient to introduce the concept of protected field strength. This is the minimum wanted-signal field strength that will be protected against the interference and is equal to the sum, in decibels, of the protection ratio appropriate to the given type of interference, and the strength of the interfering signal.* Thus:

$$P_r = R_r + I_r$$

where R_r is the protection ratio of the r^{th} interfering signal, in dB,

I_r is the level of the interfering signal, in dB(μV/m),

and P_r is the protected field strength, in dB (μV/m), with respect to the r^{th} interference acting alone.

If we now define W_r by $P_r = 10 \log_{10} W_r$, and write $P = 10 \log_{10} W$ for the protected field strength for the combined interfering signals, the power addition law gives

$$W = \sum_{r=1}^{r=n} W_r$$

or, if each power is normalized with respect to one of the signals, say W_1,

$$\frac{W}{W_1} = \sum_{r=1}^{r=n} \frac{W_r}{W_1}$$

In terms of the resultant protected field strength P, in dB (μV/m), this can be written as

$$P - P_1 = 10 \log_{10} \sum_{r=1}^{r=n} 10^{0 \cdot 1(P_r - P_1)}$$

Following from this result for unrelated interference, it is convenient to approximate the law for related interferences by a similar expression, so that

$$P - P_1 = \alpha + \beta \log_{10} \sum_{r=1}^{r=n} 10^{0 \cdot 1(P_r - P_1)}$$

where $\alpha \to 0$ for a large number of tests.

The values of α and β required to give a least-squares best-fit curve to the data of Tests 1 to 6 have been calculated, together with the corresponding errors, and the results are given in Table 2.

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* For the present purpose, the effect of directivity of the receiving aerial is not taken into account.

TABLE 2

Test No.	α	β	R.M.S. error dB	Max. error dB
1	–0·76	13·26	0·58	0·86
2	0·34	20·60	0·83	1·09
3	1·21	16·95	0·38	0·72
4	–1·08	14·22	0·43	0·72
5	–1·02	15·18	0·37	0·54
6	1·71	15·25	0·52	0·96
Mean	0·07	15·9	0·52	0·81

The mean values of α and β for the six tests are

$\alpha = 0{\cdot}07$

$\beta = 15{\cdot}9$, with a standard deviation of 2·4.

For related interferences at a subjective impairment level of grade 3 to 3·5, it is therefore suggested that the protected field strength for multiple interferences is given to a reasonable accuracy by taking $\alpha = 0$, $\beta = 16$.

In order to assess the dependence of the law upon the level of the interference, another test was carried out, with the same test conditions as for Test 4, but at a reference interference of 5 dB less. The results are given in Table 3.

TABLE 3

No. of interfering signals	Mean change in level, dB, required to produce same subjective impairment as reference
1	+0·29
2	–2·00
3	–4·15
4	–5·00
5	–6·43

The mean subjective impairment grading of the reference interference was 2·3. For this case,

$\alpha = -0{\cdot}54$

$\beta = 9{\cdot}6$

with an r.m.s. error of 0·26 dB, and a maximum error of 0·35 dB. This value of β is statistically significantly different from the mean value obtained for the higher level of interference, and it demonstrates that for the low interference levels, the law of addition is close to that for unrelated interferences ($\beta = 10$).

For a large number of interfering signals, it is reasonable to expect that the curve relating reduction in protection ratio to number of interfering signals should asymptote to a slope corresponding to a power addition law, but the proposed formula for grade 3 to 3·5 impairments gives a curve which asymptotes to a higher slope, such that the resultant protection ratio will be somewhat higher than necessary. In practice, it is not likely that a very large number of constant interferences will need to be considered, and it is undesirable to use a more complicated expression merely to obtain a more accurate result for large numbers. However, it may be helpful to use an empirical rule which may not be readily expressible in a mathematical form, but which provides a reasonably accurate result. Such a rule has been proposed as follows:

> The interferences are added on a power basis, after doubling the power of each interference except the first (the largest).

This rule produces a curve which asymptotes to a power addition law for large numbers of interfering sources, but which has the required relatively steep slope for small numbers.

The rule was checked against the results given in Table 1. As before, a constant was added to the results of each test to obtain a least-square best fit of the proposed curve to the given data. The resultant errors are listed in Table 4. Comparing the mean errors with those in Table 2, it is seen that the empirical rule on average provides nearly as good a fit as that previously given.

TABLE 4

Test No.	R.M.S. error	Max. error
1	0·65	0·90
2	1·04	1·90
3	0·46	0·81
4	0·32	0·56
5	0·34	0·50
6	0·63	1·16
Mean	0·57	0·97

Having established the general trend of the law of addition for the particular case of c.w. interference with two-thirds line-frequency precision offset, using a still picture, it is desirable to make a few checks on other cases including zero offset. For this purpose the author carried out a number of experiments, using his own judgement to assess the reduction in level required when two interferences are added. In these experiments, modulated carriers were used, and the monitor was fed from a laboratory receiver. It was concluded that, while particular combinations of offsets and picture content could be found requiring a reduction of up to 9 dB, a reasonable practical average was 5 dB (corresponding to $\beta = 16{\cdot}6$) for a level of interference corresponding to grade 3·5 impairment, and 3 dB ($\beta = 10$) for levels corresponding to grade 2. These results applied to 2 Hz offsets and to two-thirds line-frequency precision optimum offsets. They also applied when the interfering signals were at nearly equal pessimum offsets with respect to the wanted transmission. The fact that they applied to all these offsets, even although the absolute levels corresponding to a given degree of impairment were different is perhaps a little surprising, and suggests that the most important non-linear mechanism is physiological or psychological, rather than instrumental in origin.

It should be noted that the precision pessimum offset signals combined as related interferences only when their frequencies are equal, to within a few hertz. When their frequencies differ by greater amounts, they behave as unrelated interferences, as mentioned in Section 2.1. With non-precision offsets, the condition of nearly equal frequencies will in general occur for only a very small proportion of the time. However, such a condition would arise in the case of two or more transmissions in precision-zero relationship with each other interfering with a wanted transmission whose frequency is not precisely controlled. In this special situation, not only would the protection ratio appropriate to the non-precision case apply to each interference, but the addition law would be that discussed for related interference, so that multiple interference would be slightly worse (by up to 2 dB) than if all transmitters were not precisely controlled.

Finally, a check was made using a moving picture as the modulation on the wanted signal, the interfering carriers being modulated by the same picture, delayed by about 140 μs. The offset was two-thirds line-frequency precision optimum, with a tolerance of ±2 Hz. The picture was watched for about 10 minutes and the 'addition' assessment made at frequent intervals. The general conclusion was that a figure of 5 dB, as found for still pictures, was also a realistic value for moving-picture interferences of approximately grade 3·5 impairment level.

3.5. Summary of Proposed Laws

For convenience, this section summarizes the proposed laws for related and unrelated interferences. The law for related interferences applies only to a group of interferences for which either (i) the frequency offsets relative to the wanted signal are precision optimum ($n \pm 1/3$)-line frequency, where n is a small integer, or (ii) the interfering signal frequencies, apart from those covered by (i), are equal to one another within a few hertz. For example, two-thirds and five-thirds line-frequency precision offsets can be considered as being in a related group, and it is immaterial whether the offset frequency is above or below the wanted signal. Similarly, all precision zero offset interferences can be regarded as a related group. On the other hand, all non-precision offset interferences are to be regarded as unrelated. For all other cases, the law for unrelated interferences is applicable. In the cases where both related and unrelated interferences are present, each group of related interferences should first be added in accordance with the appropriate law; the groups can then be added together as if they were single unrelated interfering signals.

> If R_r = protection ratio, in dB, applicable to the r^{th} interfering signal for a given subjective impairment,
> I_r = level, in dB (μV/m), of the r^{th} interfering signal,
> $P_r = R_r + I_r$ = protected field strength, in dB (μV/m), applicable to the r^{th} interfering signal,

then the protected field strength, P, for n simultaneous interfering signals is given by

$$P = P_1 = \beta \log_{10} \sum_{r=1}^{r=n} 10^{0 \cdot 1(P_r - P_1)}$$

where $\beta = 10$ for unrelated interferences while, for related interferences, β varies from 10, at low subjective impairments, to 16, at grade 3·5 impairment.

For related interferences, an alternative 'rule-of-thumb' has been devised for impairments near grade 3·5. This proposes that a 'power addition' law is applied, after doubling the powers of all except the strongest interference. This can be expressed as

$$P = 10 \log_{10} \left[10^{0 \cdot 1 P_1} + 2 \sum_{r=2}^{r=n} 10^{0 \cdot 1 P_r} \right]$$

where P_1 in this case refers to the largest interference, measured in terms of protected field strength.

4. CONCLUSIONS

When considering the effects of a number of simultaneous constant-level interferences, it is convenient to divide the interferences into two broad classes, viz. related and unrelated. For example, precision two-thirds line-frequency offset interferences are considered to be related, whereas non-precision offsets are unrelated.

Methods of finding the resultant effect of such interferences have been discussed, and the results are summarized in Section 3.5.

The tests involving more than two interferences were carried out by injecting a c.w. signal into the video chain. Ideally, modulated r.f. signals should have been used but it is thought that for practical purposes the conclusions obtained would be unaffected, since the results obtained using either modulated r.f. signals or c.w. video signals were in good agreement in the case of two interferences.

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